(2)

AD-A207 936

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

DTIC FILE COPY

DTIC ELECTE APR 17 1989 S D

1b. RESTRICTIVE MARKINGS	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 89-0422
6a. NAME OF PERFORMING ORGANIZATION: Univ of Wisconsin	6b. OFFICE SYMBOL (If applicable)
7a. NAME OF MONITORING ORGANIZATION: AFOSR/NE	
6c. ADDRESS (City, State, and ZIP Code): Madison, WI 53706	7b. ADDRESS (City, State, and ZIP Code): Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR	8b. OFFICE SYMBOL (If applicable): NE
9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR-86-0025	
8c. ADDRESS (City, State, and ZIP Code): Building 410, Bolling AFB DC 20332-6448	10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
61102F	2305	C3	

11. TITLE (Include Security Classification)

(U) VORTICES IN LONG JOSEPHSON JUNCTIONS

12. PERSONAL AUTHOR(S)

Beyer

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM 15Nov85 TO 14Nov88		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research involved the study of the properties of long Josephson junction structures and the electronic device possibilities suggested by these structures. A large part of the work involved fabrication and modeling. A particular effort was made to build and to understand the basic operating mechanisms of a type of superconducting transistor, the vortex flow transistor. Thin film fabrication techniques were developed using niobium and lead superconductors. (jhd)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL: H. WEINSTOCK	22b TELEPHONE (Include Area Code): (202) 767-4933
22c. OFFICE SYMBOL: AFOSR/NE	

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

REPORT- AFOSR Grant #86-0025

VORTICES IN LONG JOSEPHSON JUNCTIONS

James E. Nordman and James B. Beyer
Department of Electrical and Computer Engineering
University of Wisconsin, Madison
Madison WI 53706

February 5, 1989

Final Technical Report for Period 15, November 1985 - 14, November 1988

Prepared for
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Bolling Air Force Base, DC 20332-6448

SUMMARY

This research involved the study of the properties of long Josephson junction structures and the electronic device possibilities suggested by these structures. A large part of the work involved fabrication and modeling. A particular effort was made to build and to understand the basic operating mechanisms of a type of superconducting transistor, the vortex flow transistor. Thin film fabrication techniques were developed using niobium and lead superconductors. Testing of these devices at high frequency was conducted to ascertain their potential for millimeter wave applications. It was shown that the device has active device characteristics to frequencies at least one tenth of a theoretical cutoff frequency. Inherent problems with low device impedance prompted studies of thin film high frequency coupling structures and a modelling study of distributed amplifier configurations which use many individual devices. Because the original fabrication techniques are not compatible with the more elaborate structure needed for these amplifiers, the development of a niobium nitride technology was begun. Two other related devices, one involving a lossy long junction and the other involving a single film weak link structure, were studied as alternatives to the vortex flow transistor. The latter structure was realized using thin films of the new high transistion temperature superconductors. A modeling study of spatially nonuniform long junction structures was also conducted.

RESEARCH OBJECTIVES

A prime objective of this research was to further the fundamental understanding of fluxons and fluxon motion in long Josephson tunnel junctions through experiment and model development. The complex and varied phenomena associated with the dynamics of these quantized flux lines (or current vortices) are dependent on junction bias, geometry, magnetic field and high frequency radiation. Previous knwoledge of the behavior of fluxons on long junctions had suggested a number of new electronic device mechanisms. Understanding such mechanisms to the extent that one can predict fundamental limits and make comparisons with similar mechanisms from other technologies required a good but simple model. An analogy with coupled pendulums, described by a nonlinear partial differential equation, the sine-Gordon equation, has contributed greatly to the understanding of long junction structures. However this highly nonlinear model can be analyzed only through perturbation techniques or simulation. Therefore, in addition to using the sine-Gordon equation directly, it was proposed to try to do device analysis by using a simplification which treats the fluxon as a particle.

A second important objective of the research was to produce reliable long junction structures in multilayer configurations. In order to make any significant progress in the understanding of fluxon behavior, it is extremely important to be able to fabricate large area junctions which have predictable characteristics and which can be probed in a variety of ways. It was proposed to begin with a niobium-lead thin film technology which could be developed quickly for individual devices. In parallel with this, an all Nb or NbN technology was to be developed which would be more compatible with the complex structures needed for practical devices.

A third important objective of this research was to understand the physical mechanisms involved in the various long junction amplifiers that appeared feasible.

The idea of a fluxon amplifier is very intriguing because the basic mechanisms suggest a very strong and unique duality with the semiconductor field effect transistor. Instead of controlling the availability of electrons in a conducting channel using the voltage on a capacitor, one controls the availability of fluxons in a junction "channel" using current in an inductor. The basic approach proposed for the study and modelling of fluxon mechanisms involves comparison of experimental observations with computer simulations and with a mechanical model. Specifically, this involves making junctions with various interesting geometries and performing volt-ampere measurements and rf and microwave coupling experiments. Behavior which is seen to be characteristic of fluxon dynamics is then looked for in linear particle models of varying sophistication.

The following specific projects were proposed for the three year tenure of this grant.

a) An investigation of long junction structures with spatial variation of superconducting penetration depth was to be carried out using NbN technology. This work included the development of an all NbN thin film junction fabrication technology.

b) A second project involved developing capability to make long all Nb junctions. This was meant to be a backup for the NbN technology and to allow fabrication of novel configurations including structures which allow fluxons to be oriented perpendicular to the films.

c) It was proposed to investigate one and two dimensional computer models based on the sine-Gordon equation and to correlate them with measured volt-ampere and high frequency coupling data on the junctions.

d) A study of amplification mechanisms of three terminal fluxon transistors was proposed using the computer models in conjunction with measurements on fabricated three and four terminal structures. This was to begin with a study of low frequency magnetic coupling to the junction structure and to progress to rf and microwave impedance and gain measurements.

RESEARCH ACCOMPLISHMENTS

The research accomplishments for the first two years of this grant have been included in two previous reports. A summary of information in these reports is given below, followed by a report on the third and final year of the grant.

Year 1

a) Modelling

Two types of models were worked upon during the first year. The first was a simulation of the one dimensional sine-Gordon equation. This was developed sufficiently to be able to show fluxon motion on uniform, lossy structures. The second was a two dimensional finite element program meant for study of the magnetic field configuration possible in the three terminal device. After considerable effort, it was decided not to pursue this further because it became increasingly evident from our experiments that meaningful simulation of the real configuration is possible only with a three dimensional model. Simple estimates were basically as accurate as the two dimensional model.

b) Fabrication

An existing Nb-Pb thin film Josephson junction technology was modified to allow inclusion of a current control line separated by dielectric layer. A cryopumped vacuum system was modified to allow fabrication of both Nb and NbN based junctions. An effort was begun to make NbN trilayer structures using MgO as the tunneling barrier.

c) Vortex Flow Transistor

The goal was to characterize the vortex flow transistor (VFT) at low and high frequencies. This device is an integral part of a proposed wideband superconducting distributed amplifier[1]. Because of its complicated geometry, determination of the detailed behavior of the VFT by analytical or computer methods is quite difficult and likely inaccurate. The approach taken in this project was to fabricate a number of different configurations of the VFT, test the VFT's in the laboratory, and compare

with first order models. To do this, a simple photolithographic mask making system was developed which allowed very fast turnaround. The low frequency measurements resulted in VFT configurations with high transresistance and reduced input inductance and feedthrough capacitance[2]. To characterize the VFT's at high frequencies, they were imbedded in a 50 Ohm system using coplanar transmission lines. Significant effort was put into designing high frequency coupling structures and a cryogenic cooler which allows close connections to external circuitry. Preliminary measurements indicated active device behavior out to 100MHz.

Year 2

a) <u>Modelling</u>

The sine-Gordon simulation program was modified to include the power loss in the superconducting films. Fine structure seen in the step behavior of our fabricated devices was attributed to reflections from junction boundaries.

We began exploring the theoretical possibilities of a modified superconducting current injection transistor (Modified SuperCIT) as the active component in a distributed amplifier. It promises larger gain per device and lower crosstalk levels.

b) <u>Fabrication</u>

A prototype all NbN vortex flow transistor was made and its operation in the vortex flow regime was demonstrated[3]. A large effort was made on the design, purchase, debugging and fixturing of a new dual ion beam-magnetron sputter depostion system which was designed to become the primary tool for NbN junction fabrication.

c) <u>High Frequency Studies</u>

A cryogenic system for measuring the radio frequency properties of the VFT was developed[4]. With this system, vector S-parameter measurements of the VFT were made[5]. The measurements were obtained for frequencies up to 100MHz on VFTs that had a calculated transit time cutoff frequency of 5 GHz. Higher frequency measurements were frustrated by crosstalk attributed to the low impedance 2-port structure in which the VFT was embedded.

Next, a unique modulation signal tagging scheme was employed that overcame the low impedance level limitations inherent to the 2-port VFT configuration. This scheme permitted the frequency response to be measured to 500MHz which is one tenth of the predicted transit time cutoff frequency[6].

Year 3

a) Device Modeling

As indicated above, two separate computer studies were attempted on long Josephson junction structures. The first was to be a study of the magnetic field configurations posed by different control line configurations. This was discontinued after less than a year because a two dimensional study was proving inadequate to predict any of the unusual behavior seen in real devices. A three dimensional study was considered too complicated for us to risk our limited resources.

The second study was concerned with the effect of spatial variations in the London penetration depth on vortex dynamics. This was accompanied by an analytical investigation, resulting in a detailed solution to the problem of a step variation in penetration depth on a long junction[7]. This work has also led to new considerations of the use of kinetic inductance to enhance r_m and to control observed multiple minor steps with the incorporation of periodic or aperiodic variations of the penetration depth. Elimination of these minor steps is very desirable for reduction of noise. Much remains to be done here, both analytically and experimentally because this initial work has been done on single fluxon behavior rather than on the flux flow regime. Although the effects of kinetic inductance were demonstrated using a very thin Nb layer in a transmission line structure[8], it is expected that significant success in the enhancement of long junction device properties will probably be possible only with the NbN structures. The large values for magnetic penetration depth in this material makes it possible to accomplish this spatial variation by making thin top film layers which are then covered in patterns with another superconductor.

Circuit modeling of a distributed amplifier using the SuperCIT was also attempted. Using the best available models it was shown that this device may be able to produce amplification with far fewer devices than the VFT[9]. This suggests that such devices should be fabricated in the future.

b) NbN fabrication studies and low frequency VFT measurements

The successful realization of single junctions using NbN led to expanded efforts[10] to develop a NbN technology capable, in the future, of producing distributed amplifier configurations and other complex junction structures. The new ion beam-magnetron sputtering system was dedicated to a study of the NbN-MgO-NbN thin film trilayer. In addition, a second vacuum system was outfitted with an rf sputtering head for deposition of silicon dioxide insulating layers. This work, although still incomplete, has allowed a more extensive study of VFT structures and their low frequency properties. Double junction structures were made with film thicknesses small enough to observe kinetic inductance effects[11]. The double junction configuration allows better comparison of low frequency magnetic coupling than the previous single junction structures. It has also allowed better estimation of maximum transresistance for this device.

Our previous experimentation, involving the interplay between various film protrusions or "ears" with different configurations and different control lines, led to the creation of devices with good transresistance (r_m) values, but with a significant capacitive coupling between the control line and the junction. It was shown experimentally that the capacitance can be significantly reduced with little effect on r_m by not passing the control line completely under the junction. Capacitance is reduced in newer configurations but remains as a problem in the realization of a usable amplifier. This work also led to a number of new questions. For example, we found that, with certain control line configurations, the value of r_m quickly reduces to zero above some maximum voltage value. This effect was not observed in the double junction structures.

c) High frequency studies

In order to test the VFT structures at microwave frequencies, it is necessary to solve very difficult problems posed by the low impedance levels of this device. Usually an active, or amplifying device can be characterized at high frequencies by measuring its four terminal scattering matrix parameters. Unfortunately, the important parameters for this device are masked by parasitic impedances. There are sophisticated techniques for electrically "de-embedding" devices from their surroundings, however, after considerable effort during the early stages of this grant, it was decided that the ratios of parameter values are too large to make this technique practical. Consequently, we concluded that meaningful testing of the device as an amplifier at high frequencies requires a multiple VFT amplifying structure. Although a full distributed amplifier structure is not feasible with the Nb-Pb fabrication technology, it was possible to make and test a 60 junction series array which exhibited an overall transresistance which agrees with simple theory[12]. In preparation for the building of microwave structures, we have continued a parallel study of thin film impedance tapers and transformer configurations.

d) Single film strucures

Another device configuration which we have started to study is a vortex flow transistor which uses the so called Abrikosov fluxons in a superconducting film instead of the Josephson vortices in a junction[13]. The physical mechanisms are similar to the long junction device except that vortices are now produced perpendicular to a linear section of film that has been thinned and interrupted with a line of holes producing a chain of superconducting links. This device has volt-ampere characteristics which exhibit flux flow and which can be controlled by an external magnetic field or current control line. The configuration was first made using Nb and then with high T_c superconducting films provided to us by Sandia Laboratories. The motivations for this study are to understand the differences in behavior between Josephson and Abrikosov vortices and to ascertain the feasibility

of making this type of amplifying device with the high transition temperature superconductors without the need to make tunnel junctions with these materials.

PUBLICATIONS

1. D. P. McGinnis, J. B. Beyer and J. E. Nordman, "Distributed Amplifier Using Josephson Vortex Flow Transistors," Jour. Appl. Phys. 59, 3917, (1986).

2. D. P. McGinnis, J. E. Nordman and J. B. Beyer, "Optimization of Circuit Parameters for the Vortex Flow Transistor," IEEE Trans. MAG-23, 699 (1987)

3. J. S. Jan and J. E. Nordman, "Characteristics of an all NbN Vortex Flow Transistor," extended abstracts of 1987 International Superconductivity Electronics Conference.

4. D. P. McGinnis, J. B. Beyer, and J. E. Nordman, "A Cryogenic System for RF Measurements on Superconducting Vortex Flow Transistors," IEEE Trans. on Instr. & Meas., ISSN-37., 274-276, (1988)

5. D. P. McGinnis, J. B. Beyer and J. E. Nordman, "Vector S-Parameter Measurements of the Superconducting Vortex Flow Transistor," IEEE Trans. on Elect Dev., ED-35, 240-244 (1988)

6. D. P. Mc Ginnis, J. B. Beyer and J. E. Nordman, "Gain Measurements of the Superconducting Vortex Flow Transistor at High Frequencies," J. Appl. Phys., 8, 2828-2830, (1988)

7. M. F. Petras and J. E. Nordman, "Perturbative analysis on long Josephson junctions having uniform bias and spatially varying penetration depth," to be published in Phys. Rev. B.

8. G. K. G. Hohenwarter, J. S. Martens, J. B. Beyer, J. E. Nordman, and D. P McGinnis, "Design of Variable Phase Velocity Kinetic Inductance Delay Lines and Their Measured Characteristics When Fabricated by a Simple Nb Based Process," To be published in IEEE Trans. on Mag. MAG-25.

9. D. P. Mc Ginnis, J. B. Beyer and J. E. Nordman, "A Modified Superconducting Current Injection Transistor and Distributed Amplifier Design," To be published in IEEE Trans. on Mag. MAG-25.

10. M. F. Petras, "The Ellects of Target Nitridization on the Properties of DC magnetron Reactively Sputtered NbN Thin Films, submitted to Thin Solid Films.

11. J. S. Jan and J. E. Nordman, In preparation.

12. D. P. Mc Ginnis, M. A. Ketkar, J. B. Beyer and J. E. Nordman, "Experimental Results on a Multi-element Vortex Flow Transistor Amplifier," presented at the Applied Superconductivity Conference, San Francisco, 1988. To be published in IEEE Trans. on Mag. MAG-25.

13. G. K. G. Hohenwarter, J. S. Martens, D. P. McGinnis, J. B. Beyer, J. E. Nordman, and D. S. Ginley, "Single Superconducting Thin Film Devices for Applications in High T_c Materials Circuits," To be published in IEEE Trans. on Mag. MAG-25.

CONFERENCES AND MEETINGS

1. Publication #1 above was originally presented at the Applied Superconductivity Conference, Baltimore, Sept., 1986

2. J. E. Nordman, "Novel Three Terminal Devices," Air Force Applications of Cryoelectronics-Symposium, Wright-Patterson AFB, October, 1986.

3. Publication #3 above was presented by J. E. Nordman at the International Superconductivity Electronics Conference, Tokyo, 1987.

4. J. E. Nordman, "Superconductor Distributed Amplifier Configurations," Invited presentation at Workshop on Superconductive Electronics: Devices, Circuits and Systems, Coto de Caza, California, 1987

5. Publications # 8, 9, 12, 13 above were presented at the Applied Superconductivity Conference, San Francisco, 1988

PERSONNEL

J. B. Beyer, Professor

J. E. Nordman, Professor

D. P. McGinnis, graduate student Research Assistant and Post-Doctoral Fellow

Jin-Shyong Jan, graduate student Research Assistant

Michael Petras, graduate student Research Assistant

Mohan Ketkar, graduate student Research Assistant (one year)

David Dawson Elli, graduate student Research Assistant (one semester)

Jon Martens, Graduate Student Fellow (not funded by grant)

K. Audenaerde, Professor, SUNY, New Paltz (one Summer only)

Timothy Hoeller, graduate student (one Summer only)

DEGREES

D. P. McGinnis, PhD, May 1987, "Applications of the Superconducting Vortex Flow Transistor"

M. F. Petras, PhD, December 1988, "Fluxon Propagation on Spatially Inhomogeneous Long Josephson Junctions"